OTM - An Advanced Oxygen Technology for IGCC

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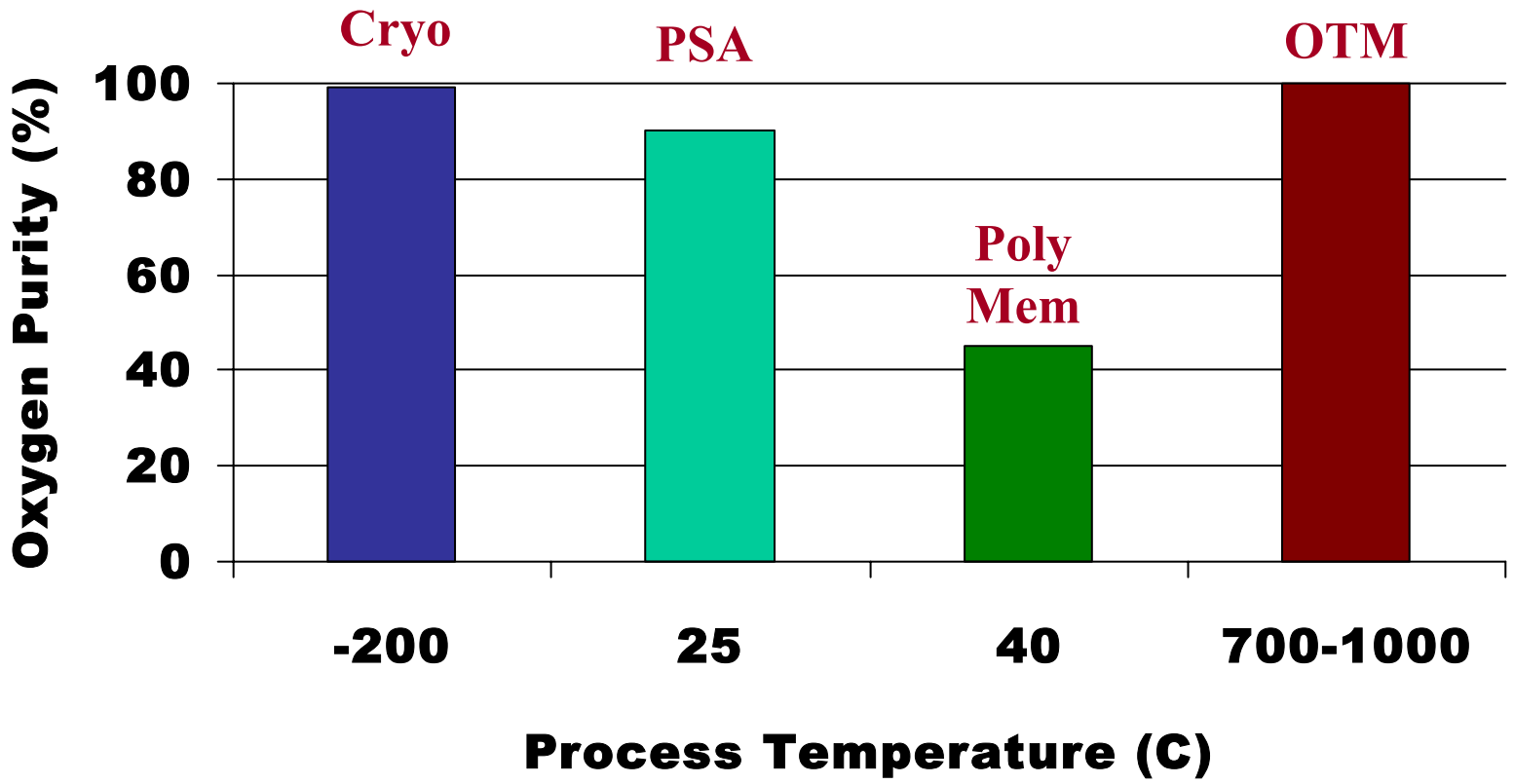
www.praxair.com

Use of Oxygen in IGCC

- **Oxygen is the preferred oxidant**
  - ⇨ Reduced costs for gasifier, heat recovery, acid gas removal
  - ⇨ Enhanced potential for CO_2 sequestration
  - ⇨ But added cost for ASU

- **O2 supply options:**
  - ⇨ Cryogenic: Most mature & commercial
  - ⇨ PSA: Small-medium sizes
  - ⇨ Polymeric Membranes: Small, low purity
  - ⇨ OTM: Emerging breakthrough technology

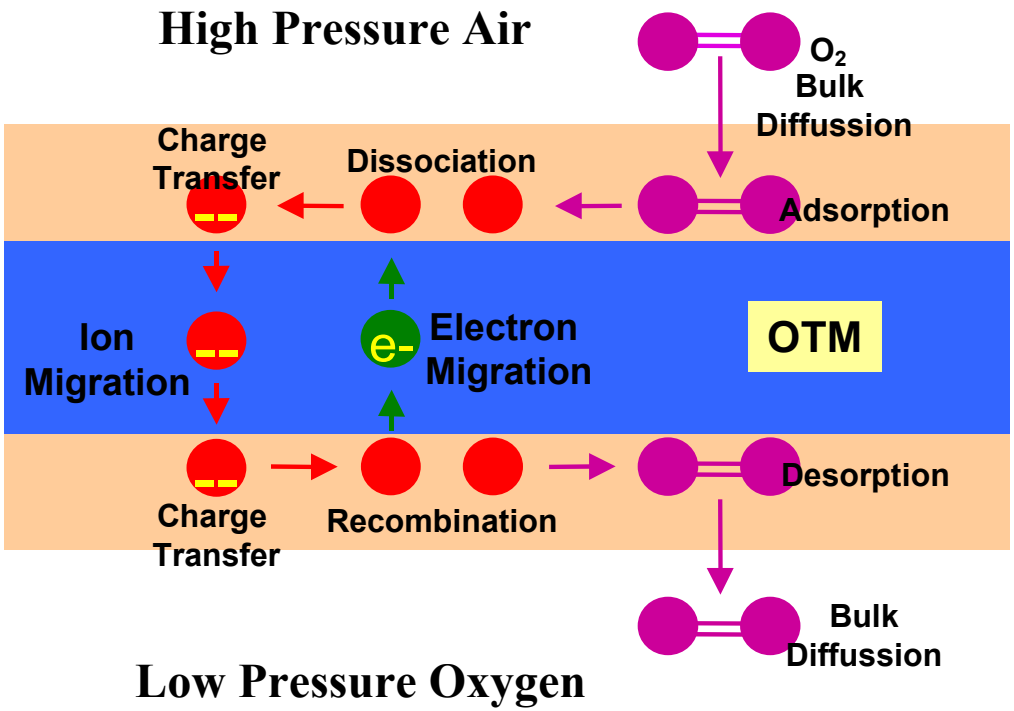
Why OTM?



High operating temperature enables efficient integration with IGCC

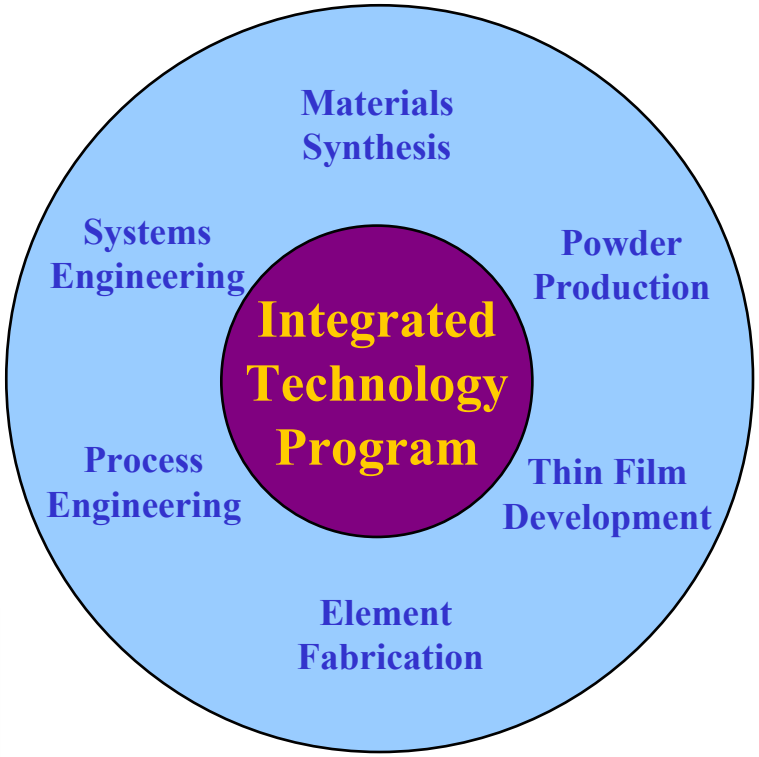
OTM = Oxygen Transport Membrane

Mixed Conductor Transport Mechanism



- Oxides of Metals
- Oxygen Ion & Electron Transport
- Produces Pure O2
- High T Operation (500-1000°C)
- Pressure Driven Oxygen Separation

Praxair's Integrated OTM Approach

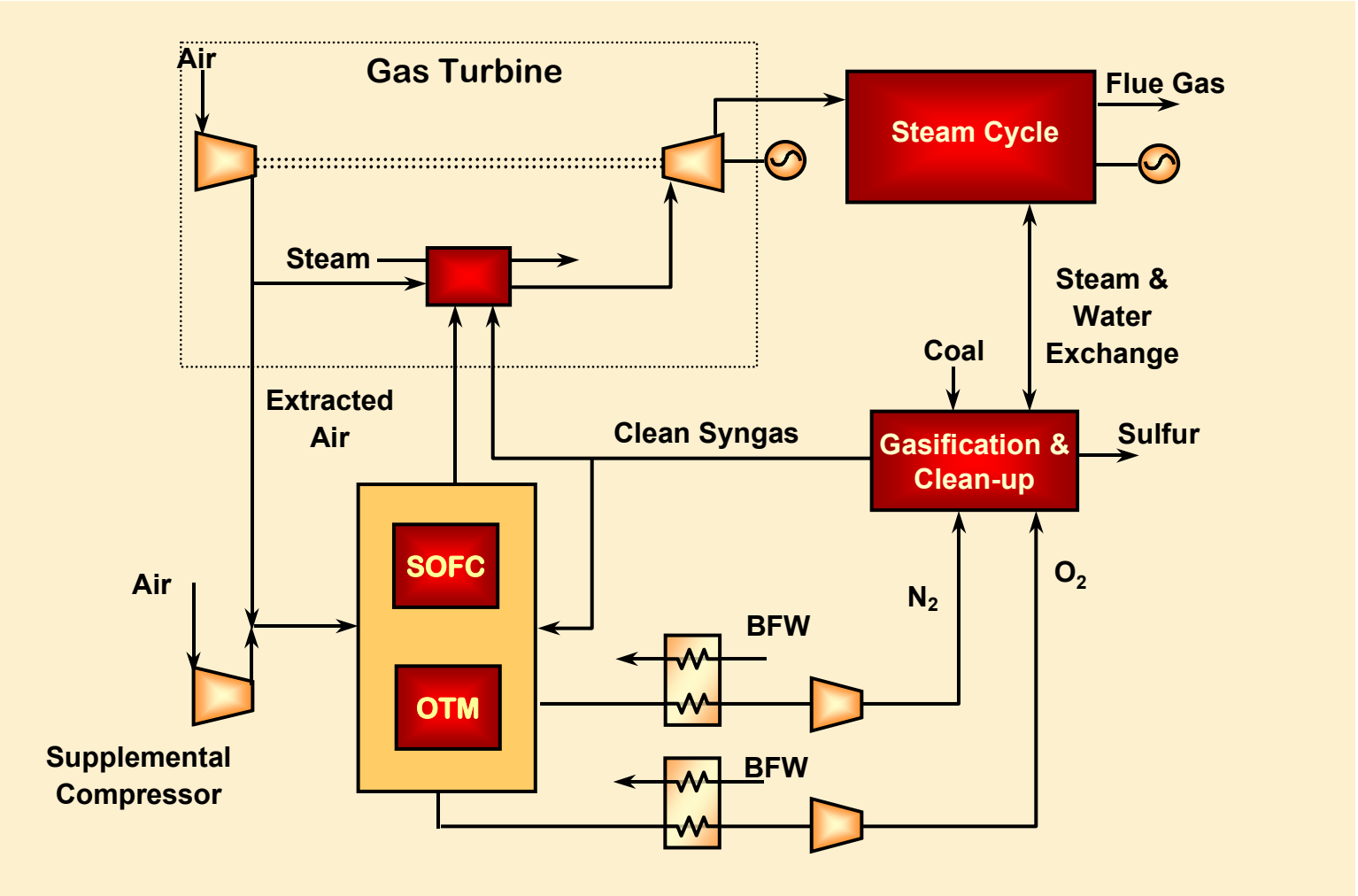


Over 25 Development Partners

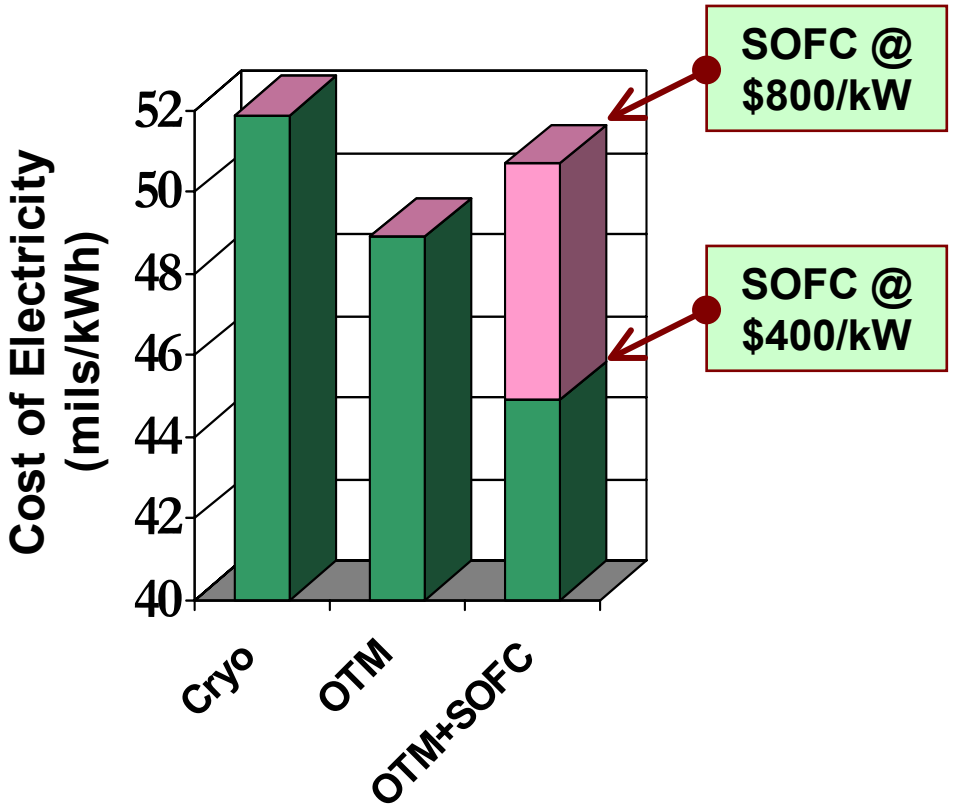
OTM Integration in IGCC Basis for Assessment

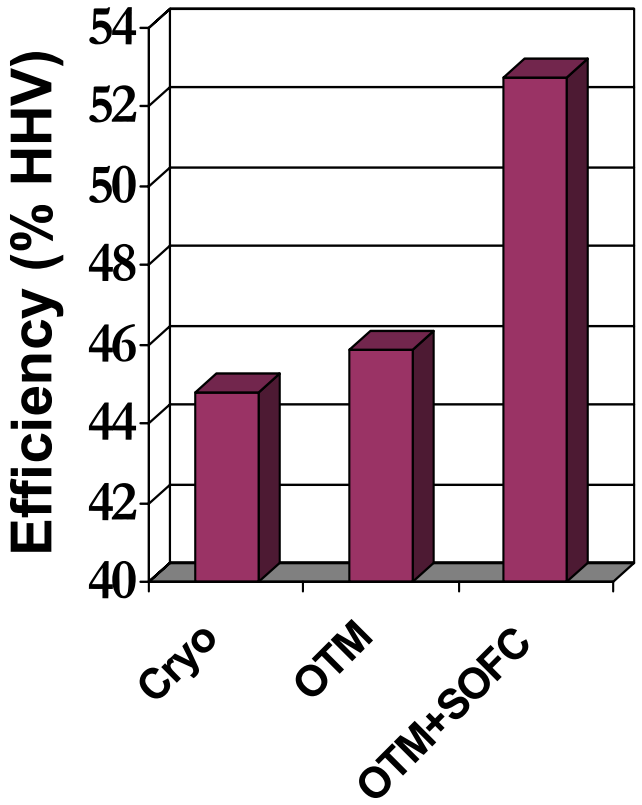
- **Illinois #6 coal as feedstock**
- **Westinghouse 501G gas turbine**
  - ⇨ Anchor point for all calculations : ~272 MW power output from GT
- **Shell technology used for gasification**
- **O_2 production:**
  - ⇨ Advanced Cryo: Advanced cryo tailored for IGCC
  - ⇨ OTM integrated with GT
  - ⇨ OTM+SOFC Integrated with GT
  - ⇨ OTM with steam integration

IGCC with OTM and SOFC



Cost and Efficiency of Power Generation via IGCC



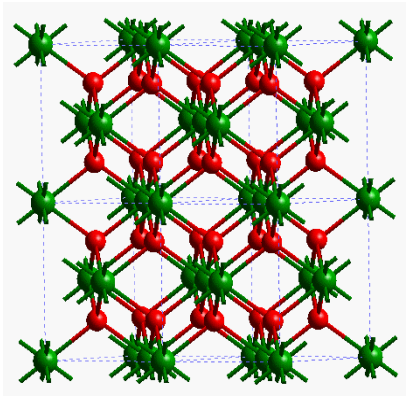


OTM integration with IGCC produces significant benefits to environment and consumer

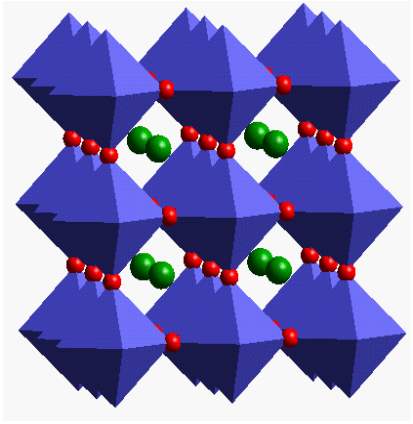
Project Plan

- **Joint DOE/Praxair program objective:**
  - ⇨ Commercialize OTM membranes for IGCC Applications
- **Phase1: 1999 - 2002**
  - ⇨ Material development
  - ⇨ Composite OTM development
  - ⇨ Proof of concept in multi-element pilot reactor
- **Phase2: 2002 - 2004**
  - ⇨ Manufacturing of full size elements
  - ⇨ Development of specialized components
  - ⇨ Engineering validation in larger pilot reactor
- **Phase3: 2004 - 2007**
  - ⇨ Pre-commercial demonstration

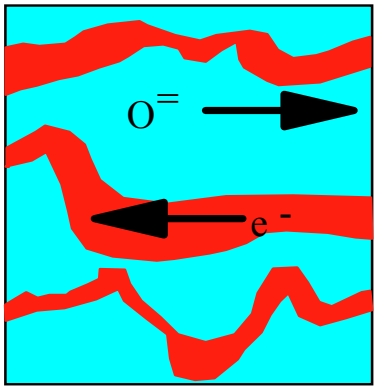
OTM Materials Options



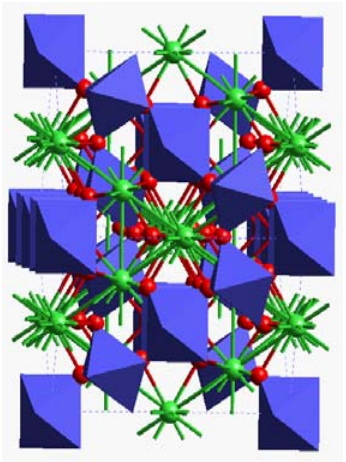
Fluorite, AO_2



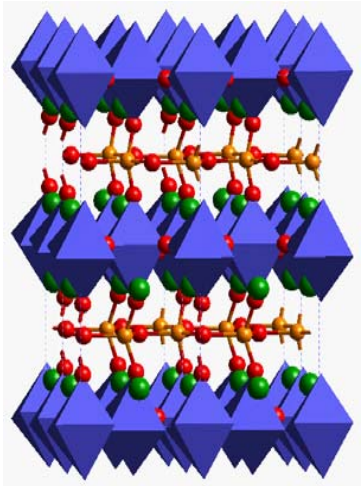
Perovskites, ABO_3



Dual Phase

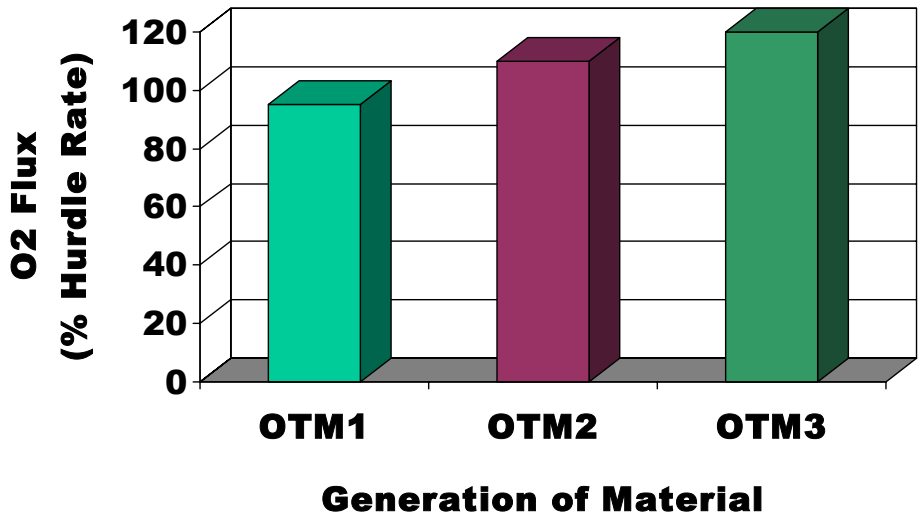


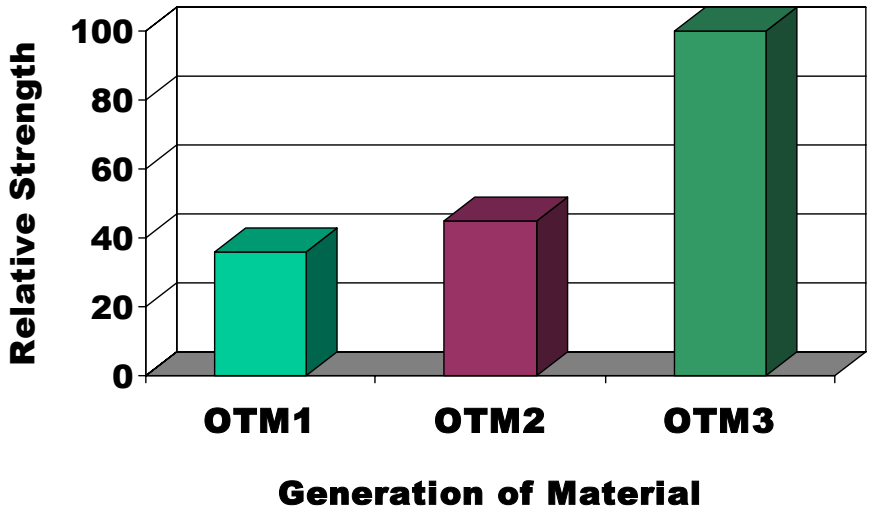
Pyrochlores, $A_2B_2O_7$



Brownmillerite $A_2B_2O_5$

Evolution of Advanced OTM Materials

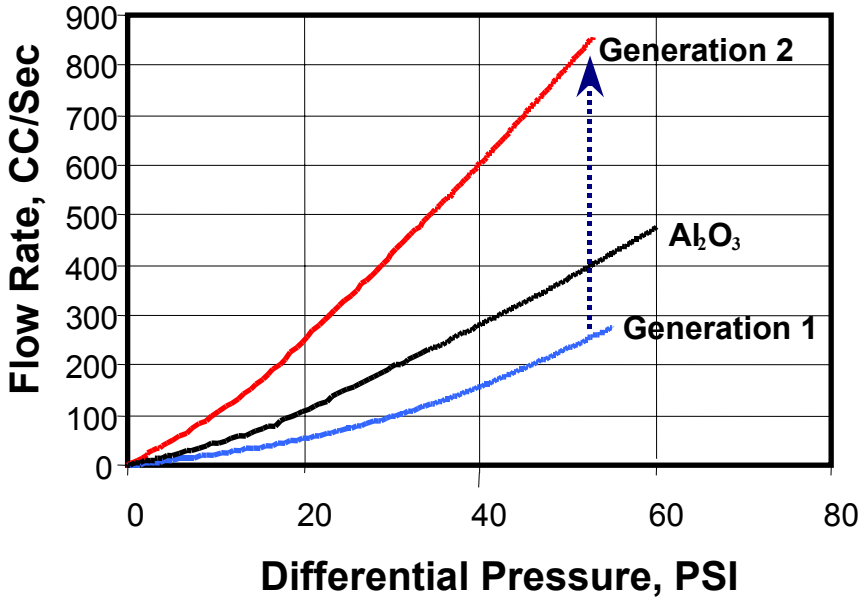




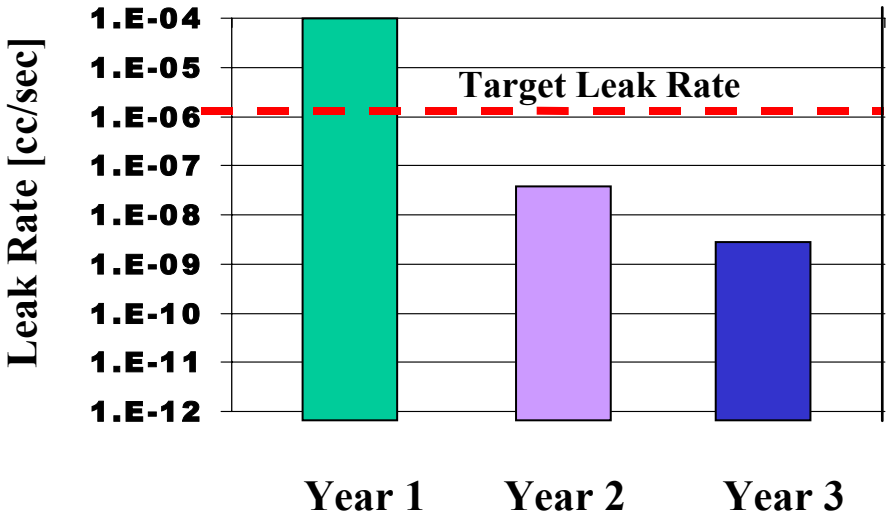
•Simultaneous improvement of flux & strength is a significant accomplishment

Components of Praxair's High Performance Composite OTM

Low resistance Substrates



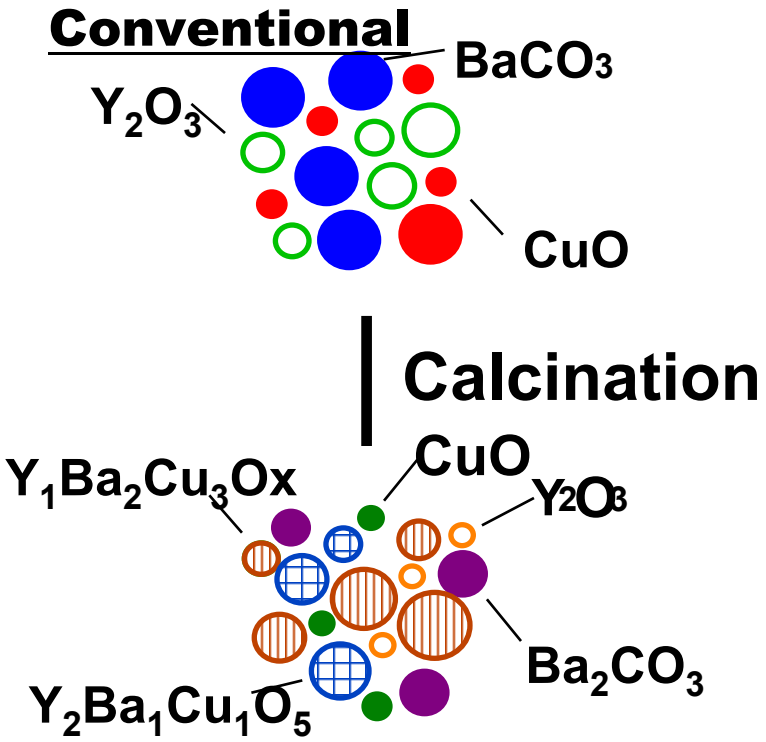
Gas Tight Films

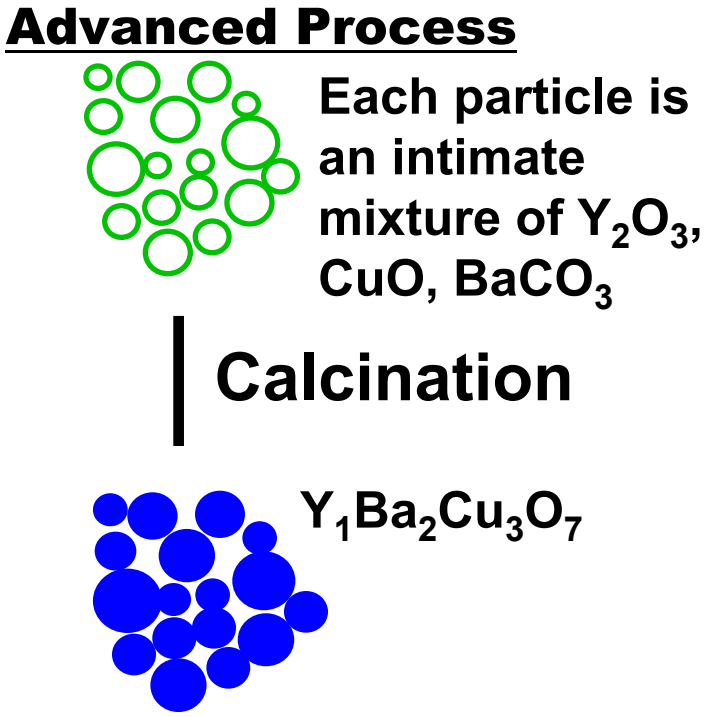


Ultra low leak rates achieved in a single firing step

PSC: Commercial Technology for OTM Powder Production

PRAXAIR





- Micro-scale stoichiometry control
- Well suited for complex, multi-cation chemistries
- Highly flexible - Over 400 mixed oxide compositions made

Element Fabrication

- **Praxair has access to fabrication technology from**
  - ⇨ Amoco
  - ⇨ BP
  - ⇨ Statoil
  - ⇨ Westinghouse
- **Praxair & its partners have fabricated and tested a wide range of element geometries**
  - ⇨ Plates, monoliths, tubes….
- **Final selection is based on many considerations**

Assessment of Element Geometry

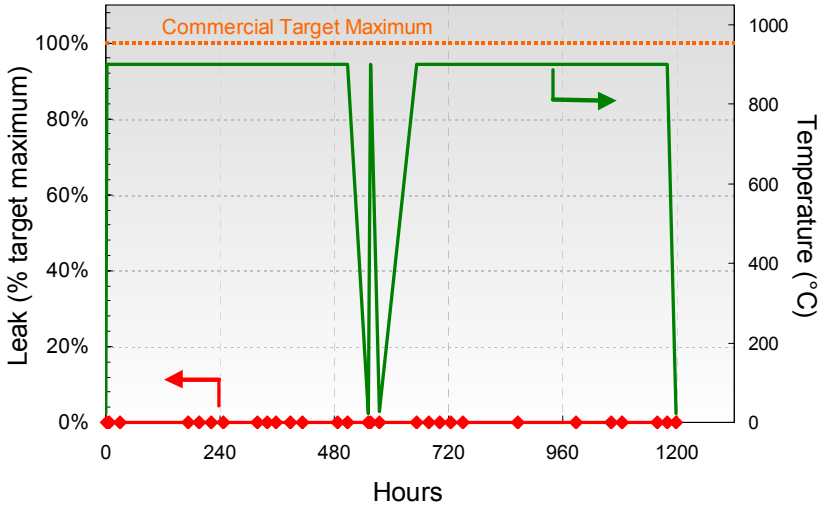
Attribute	Tubular	Planar	Monolith
Sealing	Best	Difficult	Very Difficult
Manifolding	Easier	Difficult	Very Difiicult
Strength	Self Supporting	Not self supporting	Could be self supporting
Fabrication	Existing Technology Multiple Options Most advanced for large size	Existing technology for small size Difficult for large size	Very Difficult for any size
Scaleup	Easy	Difficult	Very Difficult
Mnf Yield on Functional Element	High	Low for complex geometry	Low
Area/Volume Ratio	Medium	High	Very High
Thermal Management	Easy	Fair	Difficult
Replacement	Single tube	Entire stack	Entire Monolith

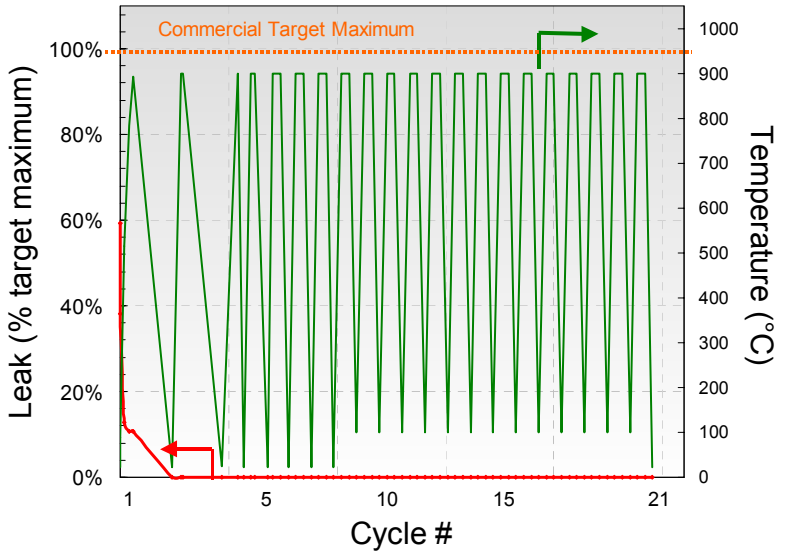
Tubular Variants: Preferred configuration

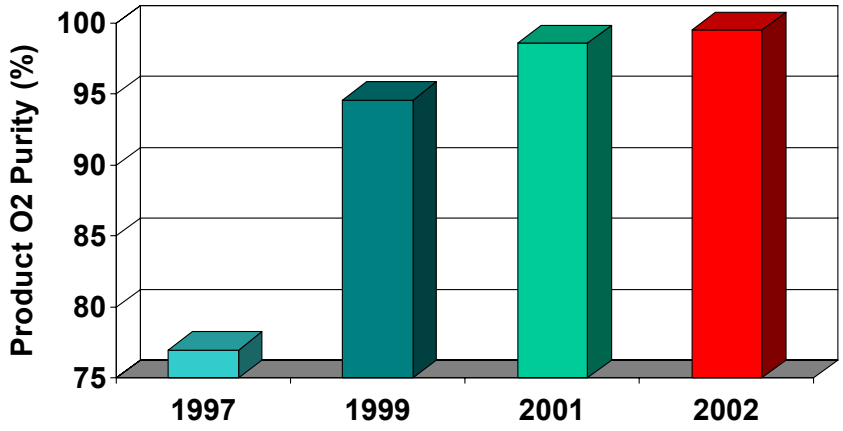
Praxair Technology for Large OTM Elements

Unique semi works manufacturing facility operational

Seal Technology Development at Praxair



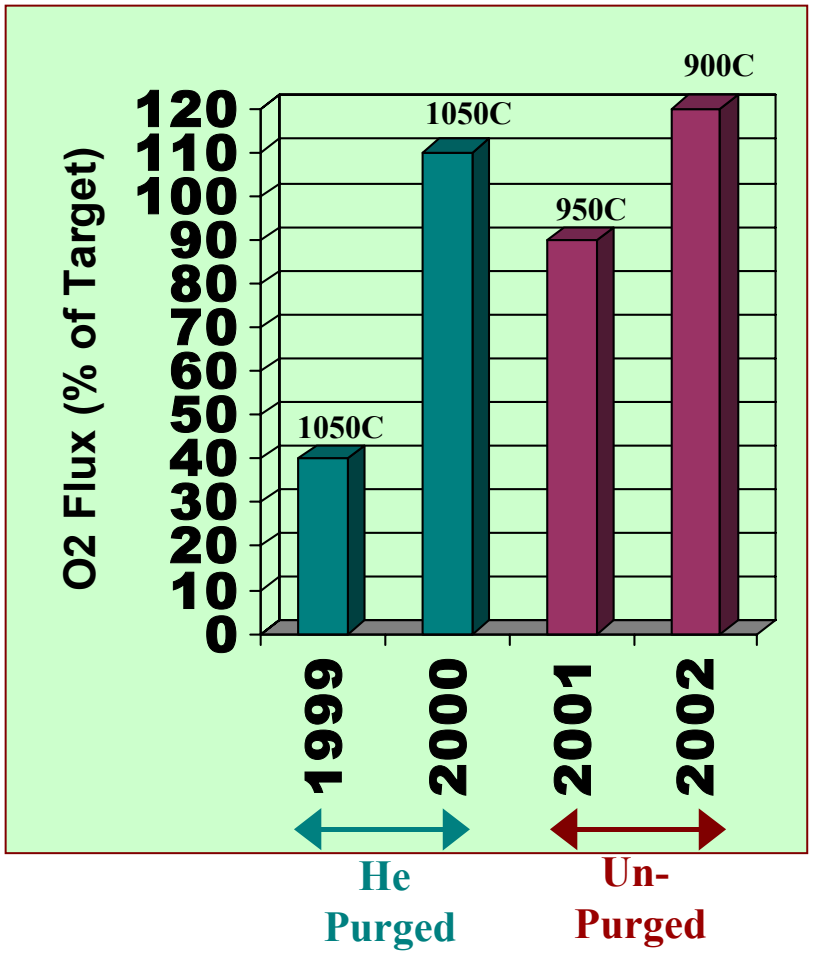




Multi-Element Pilot Reactor

- 0.2 TPD capacity
- Pilot plant producing high purity O2 using composite tubes
- Target Flux demonstrated
- Life test in progress

Advances in OTM Technology at Praxair



- **120% of target flux achieved @ 150C lower temperature**
  - ⇨ 6x flux improvement
- **Oxygen purity > 99.5%**
- **Successful 1000+ hr life test @ 275psi & 900C**
  - ⇨ Thin Film Membrane
  - ⇨ Stable flux performance
  - ⇨ No membrane degradation
- **10 thermal cycles (25-900C at 275 psi) achieved with no degradation**

Summary

- **Ceramic membranes offer potential for low cost oxygen**
  - ⇨ Lowest capital cost, power consumption, and oxygen cost
  - ⇨ 2-7% gain in efficiency
  - ⇨ COE reduction of 8-15%
- **Project has made substantial progress**
  - ⇨ 120% of commercial flux achieved
  - ⇨ High pressure cyclable seals & gas tight membranes
  - ⇨ 99.5%+ O_2 purity reached at 275 psi ΔP
  - ⇨ Multi-element pilot system operational
- **Pilot and pre-commercial demonstrations are essential steps to commercialization**